

Response to Reviewer 2

<https://doi.org/10.5194/egusphere-2026-2761-RC2>

Thank you for your constructive feedback on our manuscript, in particular the ocean modelling component. As suggested, we have re-framed the paper to set expectations around its content, more clearly explaining the model's purpose (simulating MCB, with possible other applications) and that the validation is focused on aerosol fields over the reef. Please see our responses to each comment below.

General comments

1. The code describes a regional couple model developed primarily to study the impact of atmospheric aerosols on the Australian Great Barrier Reef. In its present form the paper contains too much on the development of the aerosol code and contains too little on the ocean model and the way in which data from a relatively coarse (4km) grid was used to predict ocean properties in the shallow lagoon, shallow reef front and deep reef front zones of individual reefs. The description of the model forcing and coupling also needs attention.

I have no useful experience of aerosol or biogeochemical modelling so have not commented on the details in the related sections.

We have revised the Abstract and Introduction to clearly state the focus of the paper – to describe a simple coupled modelling system that is designed to assess MCB (with many other possible applications) and evaluate the model skill, with particular focus on aerosol fields.

We have included a detailed description of the model setup for simulating aerosol and revisions that have improved the aerosol low bias, as we think that these results are of scientific interest to the GMD community. Aerosol biases are a large source of uncertainty in climate model projections, in particular over the Southern Hemisphere oceans. While our revisions may be specific to the GBR region, the findings may be applicable to other regions too.

The description of the model forcing and coupling has also been revised, as suggested below.

Major comments

1. Line 1 Title. The model is designed primarily for studying the impact of aerosols and the validation section is primarily about aerosols. This needs to be apparent from the title.

The model is intended to study the impacts of marine cloud brightening on the underlying coral reef (primarily through changes in light and temperature), but could be used for various other studies such as the effect of aerosol deposition on marine biogeochemistry or marine emissions on aerosol and cloud microphysics. Rather than trying to explain this in the title, we have revised the Abstract to clearly state the focus of the paper:

“Here, we describe the model as configured for the GBR region, including the coupling framework, and evaluate the model skill in simulating measured aerosol, meteorology and seawater temperature and irradiance. While meteorology and seawater temperature and

irradiance were reasonably well captured by the model, a large aerosol bias was identified. The model description and evaluation largely focuses on addressing the aerosol bias, which is a key requirement for assessing the impacts of regional climate interventions such as MCB. We configure the model aerosol scheme...”

2. Abstract. This needs to say something about the size of the model grid.

The spatial extent of the regional atmosphere and ocean model grids is now given in the Abstract, with additional detail on the model configuration and grids provided in Table 1 (added to Section 2.1):

“The model comprises a regional configuration of the Australian Community Climate and Earth System Simulator (ACCESS) atmospheric model (the United Kingdom Met Office Unified Model) set up over the north-eastern Australian region (6 - 31°S, 141 - 163°E), coupled to the Commonwealth Scientific and Industrial Research Organisation Environmental Modelling Suite (EMS) hydrodynamic and biogeochemical model of the GBR (7 - 28°S, 142 - 157°E).”

Table 1. Summary of the ACCESS-EMS-GBR configuration, key components and revisions.

Model	Atmosphere (UM)	Ocean (EMS)
Domain	NE Aus (RAL3.2, Bush et al., 2025)	GBR4 (Baird et al., 2020)
Extent	6 - 31°S, 141 - 163°E	7 – 28.5°S, 142 - 157°E
Horizontal resolution	0.04° (~4 km)	~4 km
Grid size (x, y)	550, 625	180, 600
Vertical levels	90 (surface – 80 km)	48 (surface – 4 km)
Initial conditions	Global UM (N216)	eReefs GBR4 hindcast
Boundary conditions	Atmosphere: Global UM	Atmosphere: NE Aus
	Ocean: Merged BRAN2020-GBR4 SST	Ocean: BRAN2020 (Chamberlain et al., 2021)
	Land: JULES (Best et al., 2011; Clark et al., 2011)	Land: Observed riverine flows (Ellis, 2018; McCloskey et al., 2021; QLD Government)
Key components	Aerosol: GLOMAP-mode (Mann et al., 2010, 2012), with organic-mediated BLN enabled, and revised to include Aitken mode sea salt, a reduced SOA yield and modified activation scheme (Ghosh et al., 2025)	Hydrodynamics: SHOC
	Cloud microphysics: CASIM (Field et al., 2023; Shipway & Hill, 2012), coupled to GLOMAP-mode	Biogeochemistry: SHOC transport model, used to drive the ecology, optical, sediment, carbon chemistry and coral bleaching processes.
	Large-scale cloud: PC2 (Wilson et al., 2008)	
	Radiation: SOCRATES (Edwards & Slingo, 1996)	
Emissions	Anthropogenic: EDGAR 2022 time-slice (Crippa et al., 2024)	
	Monoterpenes: MEGAN-MACC (Sindelarova et al., 2014)	N/A
	Biomass burning: CMIP6 (van Marle et al., 2017)	

Sea salt: sea-air flux calculated using the parameterisation of Gong (2003).

PMOC: sea-air flux calculated from the GlobColor chl-a climatology (Ford et al., 2012), with revised emission mode mean dry diameter (40 nm).

DMS: sea-air flux calculated from a seawater climatology (Hulswar et al., 2022).

3. Introduction.

“Coral reefs in particular require high-resolution modelling...”.

“ACCESS-EMS-GBR is a high resolution, regional coupled atmosphere-ocean model of the GBR and provides a valuable tool to undertake these assessments, ...”.

By this stage I was expecting a reef resolving ocean grid, and when I later read “a curvilinear horizontal grid spacing of approximately 4 km”, I imagined a high resolution curvilinear fitted grid, typical of those used on coastal locations, using a 4 km grid in the open ocean and reducing to a few hundred metres around individual reefs. But no, I was wrong. You need to be clear with the reader earlier on.

We have revised the Introduction to make it clear early on that the resolution is ~4 km e.g. paragraph 5:

“ACCESS-EMS-GBR is a regional coupled atmosphere-ocean model of the GBR, with a horizontal resolution of approximately 4 km in the atmosphere and ocean, that provides...”

In the Methods (Section 2.2), we clarify that the ocean model uses a sparse coordinate system on a curvilinear grid, and the benefits of doing so:

“SHOC simulates seawater temperature... and other physical states on an orthogonal curvilinear grid in the horizontal and over 48 fixed ‘z’ levels in the vertical (1 m vertical resolution near the surface, increasing to 220 m at depth). SHOC uses a sparse coordinate system (representing a three-dimensional array as a computationally efficient one-dimensional vector) that operates only on wet cells (excluding land, the seabed and cells that are periodically dry). This system allows better representation of complex coastlines while minimising the computational expense required for a full variable-resolution curvilinear grid.”

We also note in the Methods (Section 2.2) that higher spatial resolution configurations are available and why these were not implemented here:

“While higher-resolution nested configurations of the EMS model are available, the GBR4 model was chosen to allow the GBR to be resolved at a spatial resolution suitable for assessing ocean-atmosphere interactions while also covering the entire GBR.”

And agree in Section 4.2 that ~4 km is not high enough resolution to resolve individual reef features (slope, flat etc) however, the GBR4 model is still able to capture some of the broader-scale temperature variability e.g.:

“Bathymetry and hydrodynamic processes (such as heating of shallow lagoon waters and upwelling along the reef slope) influence seawater temperature across the reef zones at sub-kilometre scales, which are not expected to be fully-resolved by the GBR4 model (~4 km horizontal grid spacing)... Despite the local variability across reef zones not being fully captured by the GBR4 model, the bias metrics indicate good overall agreement between the measured and modelled seawater temperature with latitude and depth”

4. Section 2.1.2. A history of the development of the code is not needed here. The paper would be tighter if the main text concentrated on describing just the sub-models used in the latest version of the coupled model. Notes on the development of individual sub-models, or differences with previous versions, could then be placed in an appendix or a supplement to the m/s.

We have added Appendix B “Effect of revisions to the aerosol scheme on modelled aerosol biases” and moved all results that compare the control and revised aerosol fields here, leaving the main text to focus on the final revised configuration.

We have left Section 2.1.2 in the main text, as it provides important context as to why certain emissions, parameterisations and settings were used. It is not meant to be a history of the code development, rather a description of the aerosol set up used. We are happy to discuss and revise further if needed.

5. Ocean Model and Hydrodynamics. This section needs revision. There should be more information about the grid being used. It is said to be curvilinear but I suspect it is similar to a regular grid but with a much greater computational cost. Neither the grid nor the hydrodynamics are described in Baird 2020.

Additional detail on the model grid is now provided in Table 1 (see above) and in Section 2.2:

“SHOC simulates seawater temperature... and other physical states on an orthogonal curvilinear grid in the horizontal and over 48 fixed ‘z’ levels in the vertical (1 m vertical resolution near the surface, increasing to 220 m at depth). SHOC uses a sparse coordinate system (representing a three-dimensional array as a computationally efficient one-dimensional vector) that operates only on wet cells (excluding land, the seabed and cells that are periodically dry). This system allows better representation of complex coastlines while minimising the computational expense required for a full variable-resolution curvilinear grid.”

Unfortunately Herzfeld’s paper is behind a paywall, so I cannot at the moment comment on the hydrodynamics. However the m/s could include a sentence or two explaining why it was chosen, given that whereas most of the computer requirements come from the deep ocean, most of the scientific interest is in the shallow shelf seas – where I suspect the model only includes a few levels. A brief description of the mixing and time-stepping schemes would also be useful.

A description of the hydrodynamic model is also provided on the EMS webpage: <https://research.csiro.au/cem/software/ems/hydro/structured-shoc/> (link provided in the Code Availability section) and User Guide (Herzfeld, 2025).

We have revised the ocean model description to provide an additional open access reference for the hydrodynamic model (Herzfeld, 2025), reasoning for using the GBR4 model and detail on the model time-stepping and mixing schemes:

Section 2.2:

“While higher-resolution nested configurations of the EMS model are available, the GBR4 model was chosen to allow the GBR to be resolved at a spatial resolution suitable for assessing ocean-atmosphere interactions while also covering the entire GBR. A description of the hydrodynamic model is provided in Herzfeld (2006) and Herzfeld (2025), with the biogeochemical components described in Baird et al. (2020).”

Section 2.2.1:

“The EMS Sparse Hydrodynamic Ocean Code (SHOC) (Herzfeld, 2006; Herzfeld, 2025) represents hydrodynamic processes in the GBR4 model. SHOC simulates seawater temperature, salinity, density, current velocity, mixing coefficients, sea level and other physical states on an orthogonal curvilinear grid in the horizontal and over 48 fixed ‘z’ levels in the vertical (1 m vertical resolution near the surface, increasing to 220 m at depth). SHOC uses a sparse coordinate system (representing a three-dimensional array as a computationally efficient one-dimensional vector) that operates only on wet cells (excluding land, the seabed and cells that are periodically dry). This system allows better representation of complex coastlines while minimising the computational expense required for a full variable-resolution curvilinear grid.”

and

“The barotropic and baroclinic equations are solved separately to allow the fast-propagating external gravity waves associated with the depth-integrated barotropic mode to be calculated independently of the slower-moving internal waves associated with the three-dimensional, density-dependent baroclinic mode. The GBR4 configuration described here uses a baroclinic time-step of 60 seconds, while the barotropic equations are solved every 5 seconds. Horizontal mixing is simulated using a Laplacian diffusion scheme with the rate of mixing calculated using Smagorinsky coefficients. The vertical diffusion scheme uses an implicit time-step to ensure stability in regions of high vertical resolution and implements a $k-\epsilon$ turbulence closure scheme. The impact of sub-grid scale coral reefs on flow is accounted for by treating the reef matrix as a ‘porous plate’, where kinetic energy is removed from the system via increased vertical mixing when a reef is encountered (at a rate that is dependent on the cross-sectional area of reef relative to the model grid cell), thereby simulating the obstruction of flow that naturally occurs due to the presence of reefs.”

The m/s says that the model uses Topex/Poseidon tidal data to specify sea level. This could be used as a horizontal boundary condition to the hydrodynamic model, or it could be imposed in each grid box (presumably by smoothing). The paper need to be more specific. If it is the latter, how does the code deal with the normal pattern of sea level changes due to the winds in shallow water or the propagation of meso-scale eddies in the deep ocean.

Tides are an open boundary condition. The thickness of the surface vertical layer may change to allow for changes in sea surface elevation (due to tide, winds, thermal expansion etc) e.g.

Section 2.2.1:

“The sea surface may fluctuate between vertical levels, as can the thickness of the upper-most layer to account for increases in sea surface elevation, such as can occur with thermal expansion or tidal variations. Tides are represented as a horizontal boundary condition...”

6. Coupling. Diurnal effects on the reef are very important and short-term feedbacks between the ocean and atmosphere also have the potential of being important so I am surprised that coupling only occurs once a day. The reasons for this need to be explained.

We currently use a simple coupling approach to capture heat exchange across the sea-air surface at daily frequency over the coral reef. The model is intended for use primarily to assess the implications of marine cloud brightening over months to seasonal time-scales, where coupling at daily frequency reduces computational cost while adequately capturing any heat/radiation feedbacks. We do note in the Discussion that increasing both the degree of coupling and frequency is an area for further development, particularly if the model is to be used for studies at the individual reef-scale or higher.

E.g. Section 2.3:

“Coupling at daily frequency is done to capture heat exchange across the sea-air surface and any feedbacks that may arise due to MCB, while minimising computational costs.”

And areas for further development noted in the Discussion:

“...by increasing the coupling frequency (e.g. from daily to 12-hourly), with an added computational cost, or by extrapolating the coupled sea surface fields forward through time. Alternatively, a more sophisticated coupling approach could be implemented, using a dedicated coupling system...”

I found that explanation of why the atmospheric model was run using the ocean model results from the previous day to be unclear. What in the atmosphere has a short ‘circulation time’ and what in the atmosphere is responding faster to what in the ocean?

Given the simple coupling approach used in this initial iteration of the model, either the atmosphere or the ocean model needed to run ahead of the other by 1 coupling interval (1 day). Given that the atmospheric circulation (winds, temperature, convection etc) respond to changes in, for example, sea surface temperature faster than the sea surface responds to changes in atmospheric temperature, we chose to run the atmospheric model ahead of the ocean.

“The atmosphere typically has a shorter circulation time and responds to changes in radiative forcing faster than the ocean.” – refers to the atmospheric temperature/SWR responding to changes in radiation (e.g. due to changes in aerosol emissions or cloud properties) faster than the ocean temperature or irradiance.

The last part of this section is more a report on the development program, not a description of the model. It should be moved to the discussion section on possible future improvements.

The last two paragraphs of Section 2.3 list the limitations and benefits of the simple coupling approach used, and the computational cost to run the model. We have left this section here as it is specific to the current model setup, rather than a future implementation.

7. Coupled fields. Again future developments are best placed in the discussion.

The sentence:

“A small number of variables are currently coupled, however, coupling of additional variables is possible and would be straightforward using the existing framework.”

is included here so that it is clear to the reader that while the initial iteration of the model includes only a small number of coupled variables, it provides the framework for additional variables to be coupled. We have left this sentence as is, but are happy to discuss or revise further if needed.

8. Coupled ocean fields. Should this be titled “Ocean Forcing”?

I think this is trying to explain how the coupled system deals with the fact that the ocean model covers only a small part of the ocean region seen by the atmospheric model.

However the solution, as stated in the first paragraph, seems to be that in both ACCESS-GBR (the ocean model) and ACCESS-EMS-GBR (the whole coupled model or do you mean just the atmospheric component?), SST is prescribed by data from a daily mean ancillary file. So what is the point of running a coupled model with a dynamical ocean (and later validating the ocean model SST values if the SST is prescribed?)

The next paragraph does seem to treat the ocean model SST separately, as it described a merged dataset is used to force the atmospheric model. However there remains the implication that the ocean model has an imposed SST.

We have revised the title of Section 2.4.1 to “Ocean forcing”.

This section describes the physical ocean forcing (currently only SST) datasets used to drive both the global and nested regional atmospheric models. ACCESS-GBR refers to the atmosphere-only configuration while ACCESS-EMS-GBR refers to the coupled system with both ACCESS (atmosphere) and EMS (ocean) models. We have clarified this in Section 2.4.1:

“Both the ACCESS-GBR (atmosphere-only) and ACCESS-EMS-GBR (atmosphere coupled to GBR4), configurations are forced by a daily mean SST ancillary file, that is used to calculate sea-air heat fluxes.”

The global atmosphere is forced by daily mean BRAN2020 SST (for consistency with the regional ocean model, which uses daily BRAN2020 products at the open ocean boundary). The regional atmosphere uses SSTs simulated by the ocean model within the GBR4 domain and BRAN2020 beyond the GBR4 domain (the ‘merged’ SST dataset).

SST is not prescribed in the ocean model. GBR4 uses BRAN2020 as the open boundary conditions but simulates evolving SST within the reef domain e.g. Section 2.2:

“The open ocean boundary conditions for seawater temperature, salinity, sea surface elevation and current velocities are provided by the Bluelink Reanalysis version 2020 (BRAN2020) (Chamberlain et al., 2021).”

9. Coupled atmospheric fields. Should this be titled “Atmospheric Forcing by the Ocean”?

We have revised the title of Section 2.4.2 to “Atmospheric forcing”. This section describes the atmospheric model outputs used to force the GBR4 ocean.

10. Model evaluation. As stated earlier, this is really about aerosol validation. The title should reflect this.

We have revised the Abstract and Introduction sections to make it clear to the reader that a large portion of the evaluation is focused on aerosol. The low aerosol bias is a common source of uncertainty in models and we think that our findings are relevant to GMD and add a scientific component to an otherwise description paper. As explained above, we have not tried to explain this in the title but have revised the Abstract and Introduction so that it is clear to the reader early in the paper which aspects of the coupled system are evaluated.

11. Seawater temperature and PAR. With a grid size of 4 km, there is no way that the model can estimate Heron Island lagoon and reef front variables. I can only suppose that an addition ‘sub-grid’ scale model is also used which somehow reflects how the ocean outside the reef affects the water biogeochemistry etc close to and within some typical reef complex. Whether I am wrong or not – please explain.

We also do not expect the GBR4 model to fully capture physical quantities across the reef front and lagoon, but it does capture some of the variability, highlighting the model skill despite its relatively coarse spatial resolution e.g. Section 4.2:

“Bathymetry and hydrodynamic processes (such as heating of shallow lagoon waters and upwelling along the reef slope) influence seawater temperature across the reef zones at sub-kilometre scales, which are not expected to be fully-resolved by the GBR4 model (~4 km horizontal grid spacing)... Despite the local variability across reef zones not being fully captured by the GBR4 model, the bias metrics indicate good overall agreement between the measured and modelled seawater temperature with latitude and depth.”

12. Discussion/Future developments. As a personal comment, not part of the review – I can believe that the coupled model does a reasonable job of modelling aerosols over the Barrier Reef region, but I am not convinced that the ocean model component helps very much. If you are not going to use much of the deep ocean region, then a dedicated coastal model with a grid that can give better resolution close to reefs would probably be better.

Also – I am not happy about the coupling system only exchanging fluxes at very long periods. You should implement an OASIS type system as soon as possible and try and couple at least once an hour. The extra computer overhead is comparatively minor.

We have re-framed the manuscript to more clearly explain the model’s purpose – a tool to assess the impacts of marine cloud brightening, with potential for use in other ocean-atmosphere studies over the coral reef region with some further developments.

The purpose of the simple coupling at daily frequency is to allow an assessment of the impacts of the aerosol emissions for marine cloud brightening on seawater irradiance and temperature (which would not be possible from static forcing fields alone) over months to seasons. In doing

so, we can assess changes in coral bleaching risk (during past events) using physical metrics such as DHW, or using outputs from the GBR4 coral bleaching model, such as the change in integrated reactive oxygen concentration over grid boxes containing coral.

We agree that a key area for further development is to increase the degree of coupling and frequency e.g.:

“...increasing the coupling frequency (e.g. from daily to 12-hourly), with an added computational cost, or by extrapolating the coupled sea surface fields forward through time. Alternatively, a more sophisticated coupling approach could be implemented, using a dedicated coupling system...”

Due to limited resources and software engineering support, implementing a dedicated coupling system has not been possible yet. While this is an aim for future work, the simple approach described in our manuscript may be of interest and serve as a starting point for the development of a more comprehensive regional earth system model.

Minor comments

1. Line 19 – Is the m/s describing the “ACCESS-EMS-GBR v1.0” or the “ACCESS-EMS-GBR”?

We have revised this line to read “ACCESS-EMS-GBR v1.0”.

2. Line 22 – “The model includes...”. There is confusion of models.

We have revised this line to read “The ACCESS-EMS-GBR model includes...”.

3. Line 230 – “and operates across different time-steps, meaning that they are inefficient when fully coupled”. Mangled English. You are really saying something about the optimal timesteps for each models being different and the inefficiency of running both using the shortest of the two timesteps.

Yes, we have revised this paragraph to read:

“The hydrodynamic and biogeochemical components are computationally demanding and operate across different time-steps. To improve efficiency, SHOC is run in stages, first as the full hydrodynamic model with its native time-step (seconds) and secondly in ‘transport mode’, where hourly hydrodynamic outputs are used in a flux form semi-Lagrangian (FSSL) advection scheme (Gillibrand & Herzfeld, 2016) to advect and diffuse biogeochemical and sediment tracers on an hourly time-step. The FSSL advection scheme reduces computing time, while accurately reproducing tracer distribution and mass conservation (Herzfeld & Engwirda, 2023).”

4. Line 118 – “Aerosol processes are represented by the GLObal Model of Aerosol Processes modal version (GLOMAP-mode) aerosol scheme”.

a) Clumsy use of ‘represented’.

b) Is “GLOMAP-mode” a version number, is it a shortened form of “GLObal Model of Aerosol Processes modal version aerosol scheme” or what?

Yes, “GLOMAP-mode” is the acronym used for the GLObal Model of Aerosol Processes modal version aerosol scheme, as defined in the previous sentence.

We have replaced ‘represented’ with ‘simulated’ in this sentence.